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Bunch by Bunch Profiling with a Rotating X-Ray Mask

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Abstract

Bunch by Bunch Profiling with a Rotating X-Ray Mask. CHRISTOPHER J. LEE (University of California – San Diego, San Diego, CA 92037) ALAN S. FISHER (Stanford Linear Accelerator Center, Stanford, CA 94025)

It is desirable to monitor the cross sections of each positron bunch in the Low Energy Ring (LER) storage rings of the Positron Electron Project II (PEP-II) located at the Stanford Linear Accelerator Center. One method is to pass the x-rays given off by each bunch through a scintillator, thereby studying a visible image. A rotating x-ray mask with three slots scans the beam image in three different orientations, allowing us to mechanically collect data to characterize and profile each image. Progress was made in designing the x-ray mask, researching and procuring parts, as well as advancing project plans. However, due to time constraints and difficulties in procuring special parts, the full system was not completed. A simpler setup was built to test the hardware as well as the feasibility of characterizing a circular image with a rotating mask. A blinking green light emitting diode (LED) simulated a single positron bunch stored in the LER ring. The selected hardware handled this simulation setup well and produced data that led to a reasonable estimation of the LED image diameter.

Bunch by Bunch Profiling with a Rotating X-Ray Mask

Introduction

High energy particles collide and obliterate each other at the Stanford Linear Accelerator Center (SLAC). Electrons and positrons accelerate down a two mile long linear accelerator to be stored inside two 2.2 km circumference rings of the Positron Electron Project (PEP-II). The low energy ring (LER) stores circulating positrons in more than 1700 distinct groups called 'bunches,' while the high energy ring (HER) stores electron bunches. Eventually, these two particle types collide at the interaction point (IP) within the BABAR detector. The more collisions there are in one pass, the more useful data SLAC scientists can work with. A key parameter determining the luminosity (collision rate) is the size of each beam at the IP, which in turn is related by the focusing magnets to the size elsewhere in the ring. Thus, it's of interest to somehow monitor the beam cross sections.

One way of doing this is by imaging the bunches. A charged particle moving near the speed of light radiates photons when an external force changes the trajectory. This synchrotron radiation is largely emitted as x-rays. And by passing the x-rays through a scintillator, a crystal that converts radiation to visible light, we can see the bunches. Currently the LER has a live feed x-ray pinhole camera, which monitors the *overall* cross sectional beam size; we cannot yet observe *each* bunch's size with this.

The goal is to determine individual bunch sizes. The difficulty lies in measuring 1700 bunches - with only 4.2 nanoseconds between each bunch. The nontrivial solution is to set up a camera to take a series of snapshots; however this requires putting a very costly camera, with an image intensifier and a high-speed electronic gate, into the damaging radiation environment of the tunnel. Moreover, this camera can only take 2 images per second, requiring 14 minutes to measure all the bunches.

The proposed solution builds upon *measuring* projections of the beam image; *no* snapshots are taken. It turns out the particles distribute as a Gaussian, forming an elliptical beam cross section. Mathematically we represent an ellipse in three variables: semi-major and minor axes, and the angle of inclination. By determining these three unknowns, we can construct an accurate beam image and determine the size of the beam.

We solve for the three unknowns by measuring the projection of the beam intensity along three axes. The concept is to scan the beam cross section with a disc shaped x-ray mask that is opaque to the x-rays except for three narrow slots. As the disc rotates at 1 Hz, the slots sequentially approach the beam at different orientations. X-rays passing through each slot strike a fast scintillator, and the brightness of the resulting visible light is measured with a fast photomultiplier tube (PMT). While the bunches take 7.3 microseconds to run around the ring and return to the pinhole camera, the slots barely move in comparison. But the PMT produces a pulse for each bunch passing by. By digitizing and sorting these pulses, one gets a set of points for each bunch and for each slot. These points, the intensity as a function of slot position, are fitted to a Gaussian curve. Repeating this procedure gives three Gaussian equations, which solve for the three ellipse quantities.

During the course of the project, progress was made in designing this system, but there wasn’t enough time to gather materials, build, and implement the final product. Instead, to test the project concept of profiling an image with a rotating mask, we built a similar and much simpler setup: A *two* slit wheel scanning the image of a blinking green light emitting diode (LED). The blinking simulated pulses from a single bunch passing by, allowing us to collect data with an oscilloscope rather than the fast electronics required for sorting the actual beam's 1700 bunches.

Materials and Methods

The primary components of the final system are the photomultiplier tube, a scintillator, x-ray mask wheel, a motor, and an angular encoder. As for the simulation setup, the major components are a LED, an optical lens and a two slot mask wheel. Details and selection of these components are discussed below.

A. Photomultiplier Tube And Scintillator

There are only about 4.2 nanoseconds between consecutive bunches. To collect data within this tiny window, the scintillator's emission plus the PMT's response time must add to less than 4.2 ns. This demands a small and fast PMT, plus an unusually fast scintillator. The Hamamatsu R7400P is a suitable PMT with about a 1.5 ns rise time. As for a scintillator to convert the bunch peak's 7 keV x-rays to visible light we are investigating $LiBaF_3$ (0.8 ns), $KMgF_3$ (1.3 ns), and $KCaF_3$ (2 ns).

B. X-ray Mask Wheel

The design and construction of the x-ray mask disc poses a special problem. The wheel will have a 10 cm radius, with three slots located 8.5 cm from the center and spread 15 degrees apart. The slot length will be 15 mm, and the ideal slot width would be 20 microns. Using the best x-ray absorber, platinum, the thinnest we can make the mask is 200 microns. Now, at that aspect ratio, the thickness of the slot poses a problem; the depth is longer than the width, and the slot looks like a deep tunnel. Ideally x-rays fly through a perfectly aligned 20 micron slot, and avoid hitting the walls of the tunnel. But in practice the slot will be misaligned, either from imperfectly making the slots (since machining a perfect tunnel is difficult) or the mask not being perpendicular to the x-rays. When incoming x-rays hit the walls of the tunnel, they are scattered and absorbed, reducing the x-rays reaching the scintillator. Making the slot material as thin as possible minimizes the tunnel death effect, which is why we chose the densest x-ray absorber: platinum. As for how thick to make the platinum slots, Figure 1 shows our x-ray power spectrum, and Figure 2 shows that a 200 micron platinum plate masks out almost all our x-rays.

A solid platinum wheel sounds ideal, but would be very expensive, so we took a couple of steps to minimize costs. The beam strikes only a circular portion of the wheel, so only an annular section needs to be x-ray opaque. A small platinum plate with three slots makes up a portion of this ring, and the rest consisting of 1.59 mm thick stainless steel. This x-ray opaque loop is placed on a solid aluminum circle. We expect this wheel to weight about 227 grams.

C. Motor And Angular Encoder

A New Focus Model 3501 optical chopper will rotate the wheel at a precise rate of 1 Hz. The chopper has an optical sensor to indicate the passage of each slot coupled with a controller that allows precise control of the rotation rate. We tested the motor by constructing a test wheel that had the same moment of inertia, and about 4 times the mass as the final wheel. To relieve radial load on the motor, the motor was placed face-up so the load could be placed on top, axially. The motor was able to speed up and maintain a steady 1 Hz with this test wheel, so it should be able to output enough torque for the final wheel.

To track the precise angular position of the wheel, we will attach an angular encoder to the shaft of the wheel. An angular encoder is a device that looks like a motor that outputs a digital signal corresponding to the position of the shaft. The Accucoder Model 958 is an encoder that has an angular resolution of 4096 discrete points per turn (about .09 degrees). We wrote a Labview program to observe the encoder output as a meaningful angle. Since we will read the encoder once per PEP ring turn, (the 7.3-μs time for a particle to go around the ring, giving 136,000 encoder readings in one turn of the wheel), the accuracy can be further increased by assuming that the wheel is turning at a steady rate between increments of the encoder and interpolating the position of the wheel in between each point.

D. Simulation Apparatus And Methodology

For the simulation setup, a 5 volt green LED blinking every 7.3 microseconds emulates the light pulses of a single bunch going around the PEP-II rings. Note that this LED is not an ideal Gaussian light source, but we're not too concerned since this is meant to be a rough simulation. A 100 mm focal length lens focuses this LED as a 6 mm circular image, located 49.2 mm from the center of a two-slit chopper wheel rotating at 2 Hz. The slots are 1 mm wide, set 180 degrees apart, and set to scan the image up vertically, staying parallel to the x-axis. With two slots on a wheel turning at 2 Hz, a slot scans the LED image every quarter second. A PMT, placed behind the wheel, measures the brightness of the horizontal slices of the image. With each blink, the PMT outputs a signal proportional to the brightness of the light strip. This setup is built on a 18'' optical breadboard and placed inside a 24'' black box.

For data collection, an oscilloscope is sufficient for observing the PMT output, whereas for the final project, (signal every 4.2 ns, and 1700 bunches to keep track of), a fast electronics system is needed.

Results

The results of the simulation setup are presented in Figs. 3 to 6, with each subsequent plot zooming in on features of Fig. 3. The "Slot Signal" (Fig. 3) shows the PMT blips produced each time a slot passes over the PMT (every quarter second). The peaks are negative because the PMT we're using uses a negative voltage input, hence the PMT amplifies negatively. Zooming into one peak reveals a nearly Gaussian cluster (Fig. 3) from scanning a circular image that is a Gaussian approximation. Focusing in on the details of each point we can see the contribution from the individual LED blinks (Figure 4). Again, the data from this test setup differs from the final setup since we aren't getting perfectly Gaussian peaks. But for now we will approximate our simulation clusters as Gaussian and perform a fit on them for a quick check.

Discussion

In Fig. 4, the noisy datapoints that do not follow the peak arise from the oscilloscope writing data even when the LED is off. Figure 6 compares the cleaned up data to a Gaussian Fit:

y = A*e^(-0.5*(x - B)^2/S^2) +B

"A" is the amplitude of the peak, "B" is the vertical offset, and "S" is the standard deviation; values are stated in Table 1. Taking the width of the Gaussian fit to be the full width at half maximum, which is approximately 2.355 times the standard deviation, we get a value of .0075 second. For an approximation, we imagine a point located at the image sweeping an arc. The length of this arc is:

0.007536*2 Hz *2 Slots ***PI***49.2 mm ~ **4.66 mm**

Since the LED image was a rather uniform circle instead of Gaussian, we expected a value smaller than the image diameter of 6.3 mm, which our calculations show. Again, this simulation run was only meant to demonstrate the feasibility of using a rotating mask to determine the diameter of a Gaussian image; we aren't too concerned here how accurate the diameter results are.

Future Work

Our chief concern is to continue investigating for a sub-nanosecond scintillator that can work with our low photon energies. Also we'll need to implement and program an angular encoder into our setup.

References

[1] A. Fisher. (2007, August). LER Synchrotron-Light Power for the X-Ray Monitor. [Online]. Available: http://www.slac.stanford.edu/~afisher/XRay/XrayPower/XrayPower.pdf

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Tables

Parameters	Names	Values
A	amplitude	-0.05176
B	Baseline/Offset	-0.005
S	standard deviation (sec)	0.003129

Table 1. Fitting parameters

Figures

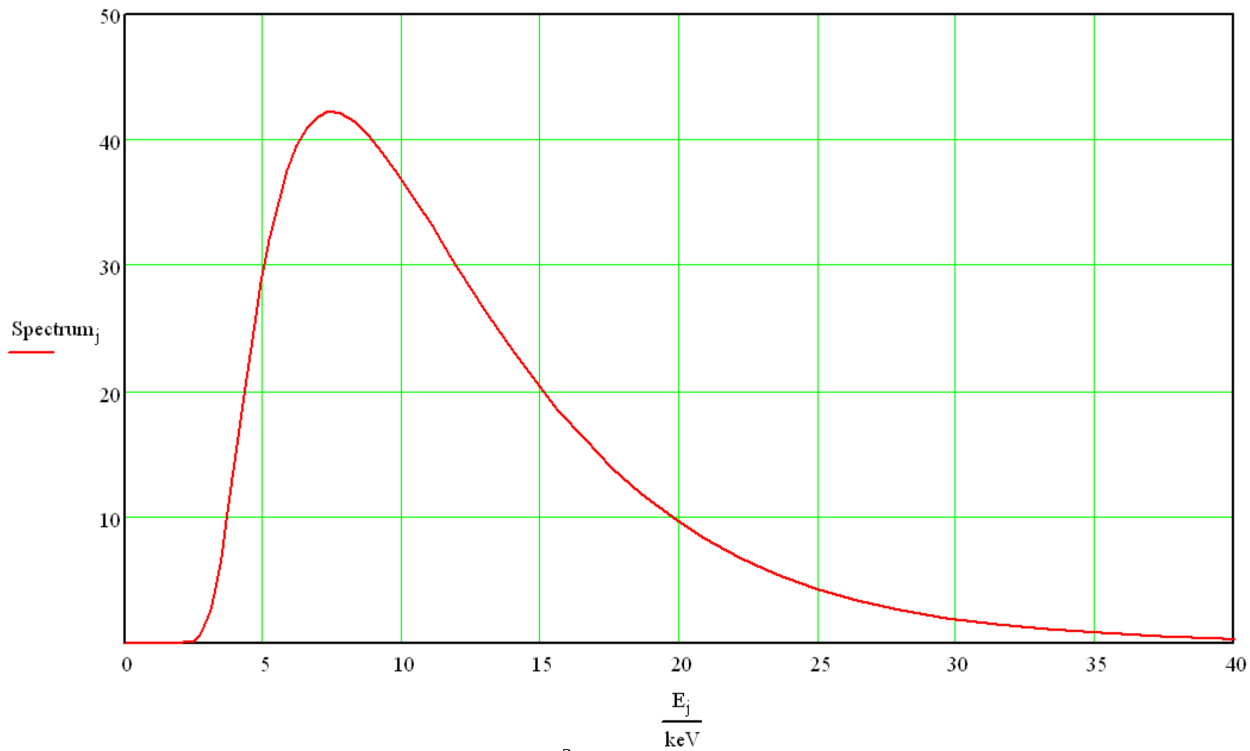

Figure 1. X-ray power spectrum, in W/(cm^2·keV), vs. photon energy in keV [1].

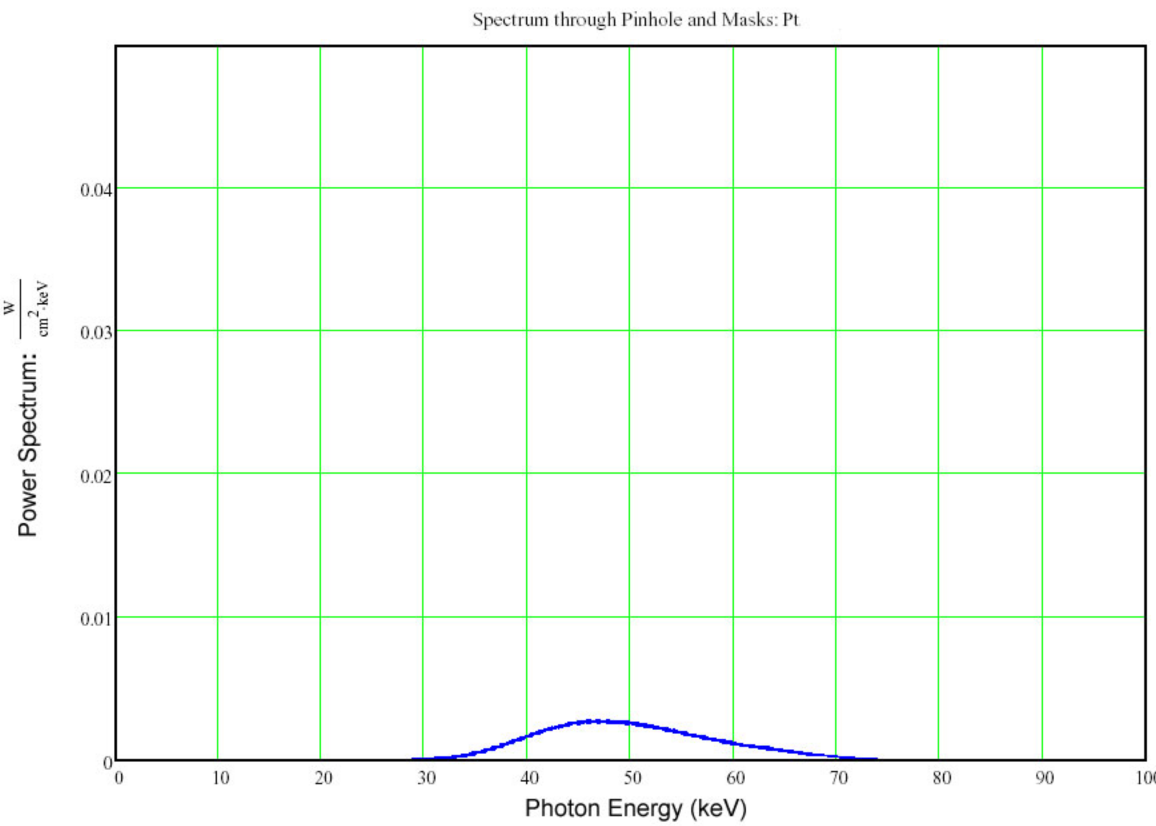

Figure 2. X-ray energy leakage through 200 micron platinum mask [1].

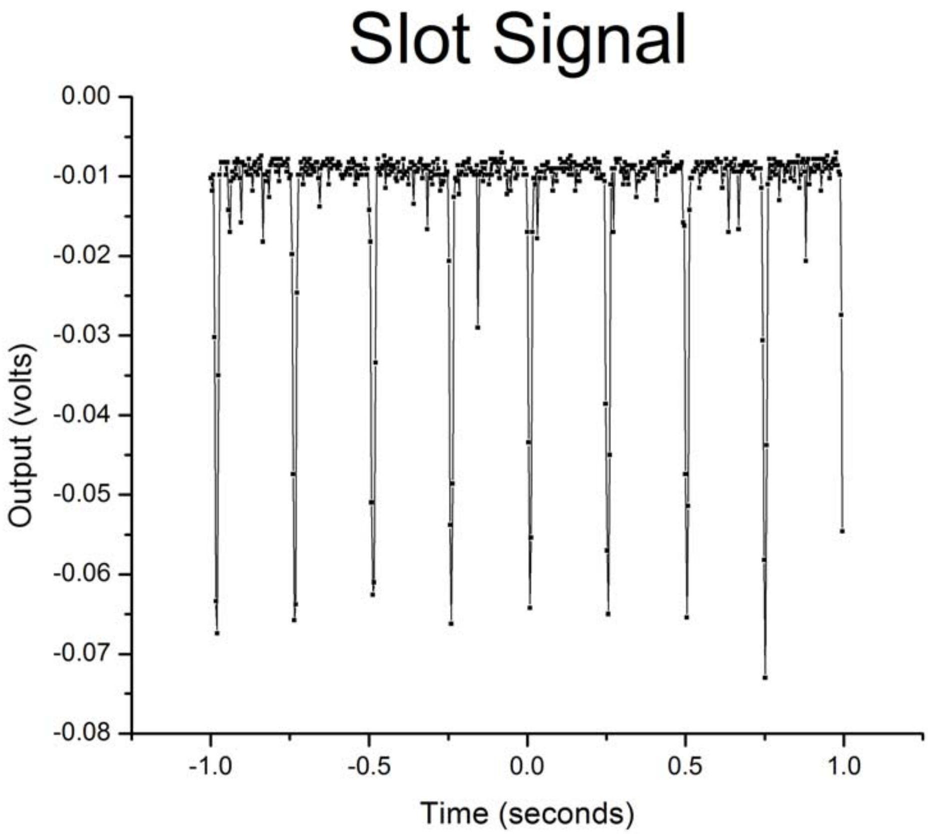

Figure 3. Photomultiplier signal as the slots pass in front of the PMT.

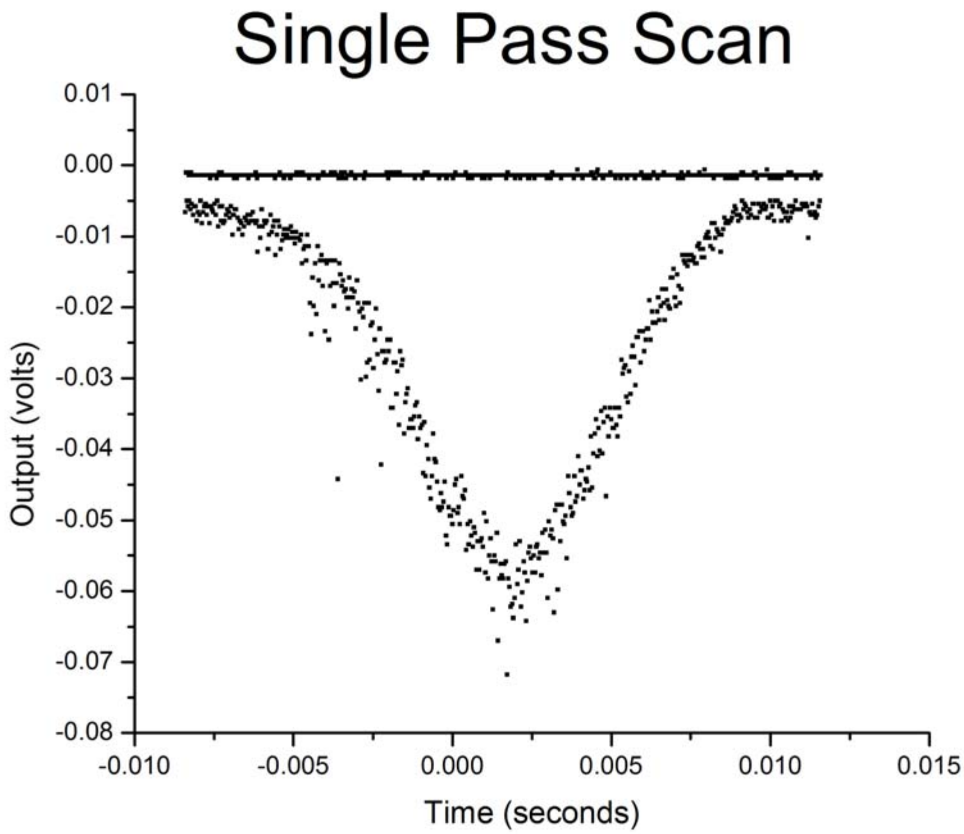

Figure 4. Photomultiplier output from a single pass slot scan of the LED image.

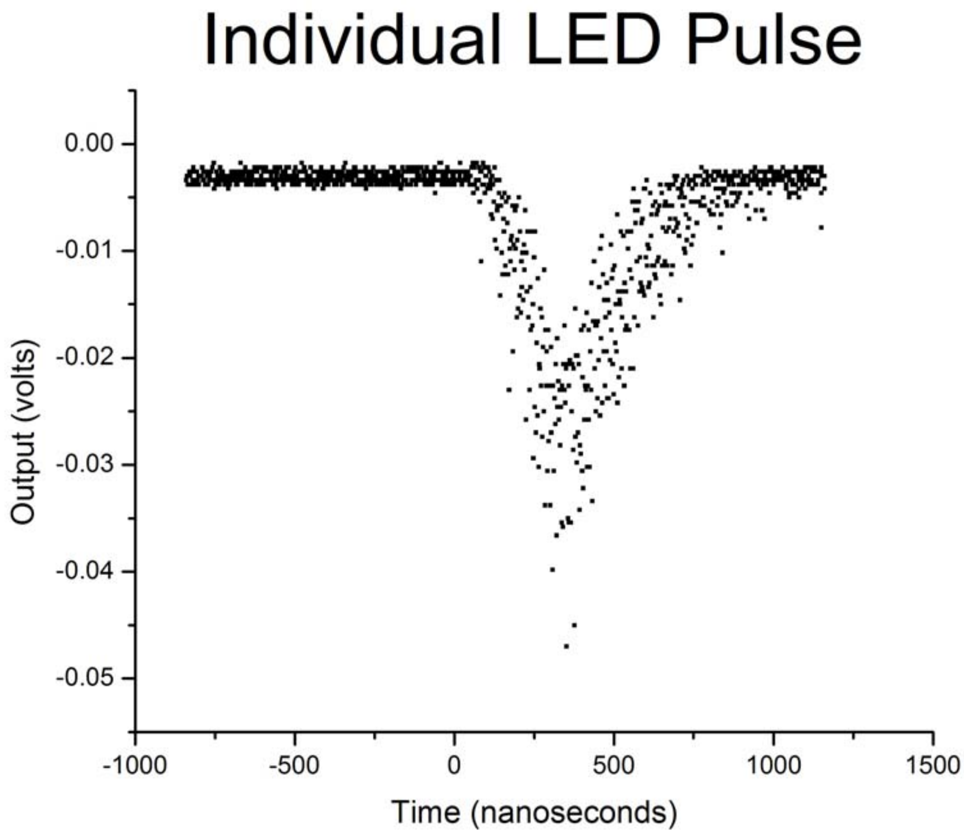

Figure 5. Pulses from each LED blink (every 7.3 microseconds).

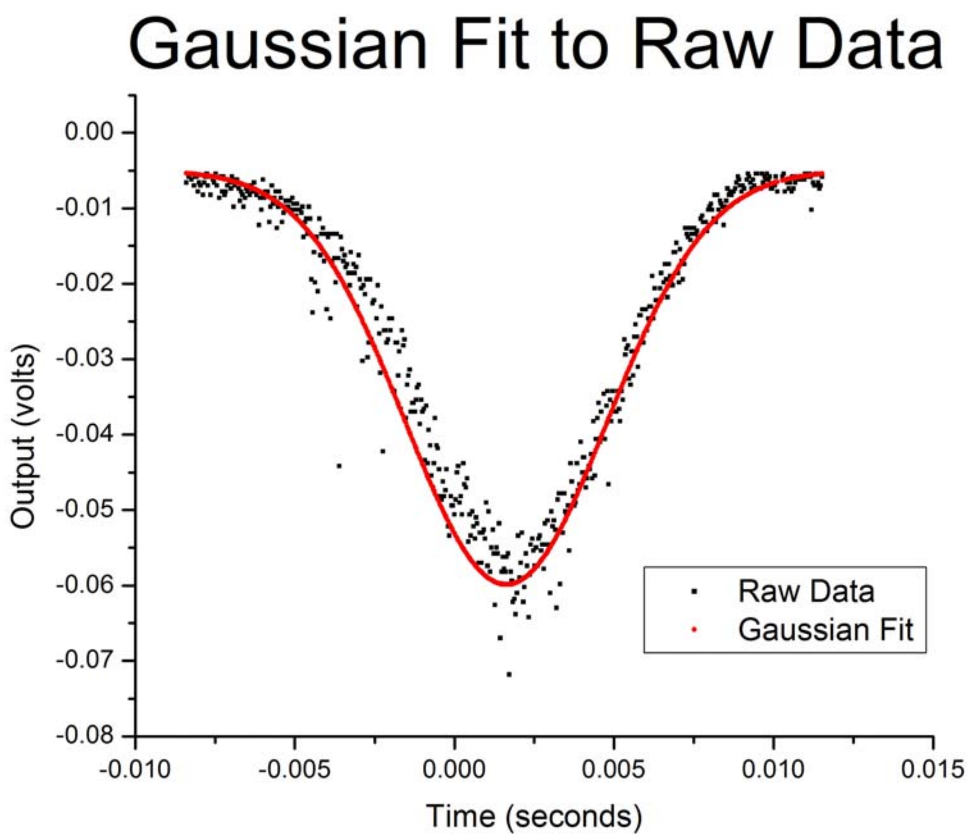

Figure 6. Gaussian fit applied to single scan. (Excluding points taken when LED was off)